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Comparison of dual crop coefficient method and Shuttleworth–Wallace model in evapotranspiration partitioning in a vineyard of northwest China

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ABSTRACT

The objective of this study was to evaluate the potential use of dual crop coefficient method in FAO-56 (FAO dual-K_c) and Shuttleworth–Wallace (S–W) model in estimating evapotranspiration (ET) and its components (plant transpiration and soil evaporation) of a vineyard in arid region of northwest China. Continuous measurements of ET with eddy covariance, plant transpiration (T) with sap flow system and soil evaporation (E) with micro-lysimeter in 2013 and 2014, were used to validate the performance of two approaches. Results indicate that sap flow system and micro-lysimeter can provide accurate measurements of T and E at hourly and daily scales if compared to eddy covariance, respectively. The FAO dual-K_c method in partitioning ET was acceptable when using the site-specific basal crop coefficient obtained from sap flow, with the slope and intercept of linear regression of 0.96 and −0.13 mm d^{-1} (R^2 = 0.81) for ET, 0.92 and −0.07 mm d^{-1} (R^2 = 0.76) for E, 0.93 and 0.16 mm d^{-1} (R^2 = 0.80) for T, respectively. The S–W model can better estimate ET, but overestimated T and underestimated E when using site-specific soil surface resistance, with the slope and intercept of linear regression of 0.98 and 0.28 mm d^{-1} (R^2 = 0.79) for ET, 0.49 and 0.42 mm d^{-1} (R^2 = 0.46) for E, 1.10 and 0.38 mm d^{-1} (R^2 = 0.81) for T, respectively. Both approaches had obvious discrepancies of E after rainfall and irrigation, especially the S–W model, and overestimated T after a snowfall. Sensitivity analysis indicates that estimated ET and its components were sensitive to soil field capacity and wilting point in both approaches, and in the S–W model, predicted T was also sensitive to leaf area index (LAI) and minimum stomatal resistance and predicted E sensitive to soil surface resistance and LAI. Thus two approaches can estimate ET with good accuracy, but the FAO dual-K_c method had higher accuracy in estimating E and T.

1. Introduction

There are abundant light resources suited for grape production, but limited water resources in the arid region of northwest China. In recent years, large areas of vineyard have been established in this region (Liu et al., 2006). Irrigation is essential to ensure grape production in such areas, and appropriate amount of irrigation water at right time directly increases wine quality (Intrigliolo and Castel, 2008). However, most of vineyard in this region is furrow-irrigated with an empirically determined irrigation quota (Zhang et al., 2011). To develop rational irrigation strategy and achieve higher water use efficiency, an accurate estimation of actual evapotranspiration is necessary (Kang et al., 2004).

Evapotranspiration (ET) can be divided into soil evaporation (E) and plant transpiration (T). In the vineyard, due to large fraction of exposed soil, soil evaporation can account for 40% of ET using furrow irrigation (Zhang et al., 2010, 2011), 30% of ET using drip irrigation (Yunusa et al., 2004; Poblete-Echeverría et al., 2012) and 77% of ET using flood irrigation (Lascano et al., 1992). And the function of E and T is different, T is associated with plant productivity, while E does not directly contribute to plant productivity (Kool et al., 2014), so T is considered as the desirable component but E as undesirable component (Agam et al., 2012). A better understanding of ET components and how much water is used through plant transpiration can help investigate if irrigation can be improved and available water can be used more efficiently (Zhao et al., 2013; Kool et al., 2014).

ET partitioning is possible using micro-meteorological measurements (Bowen ratio, eddy covariance system), eco-physiological techniques (sap flow, stable isotopes), and hydrological balance

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methods (lysimeter, soil water budget) (Kang et al., 2003a,b; Williams et al., 2004; Yepez et al., 2005; Er-Raki et al., 2010; Zhang et al., 2011). However, these techniques are often expensive and require specific equipments, thus they are limited in agricultural water management, so the estimating E and T respectively with models has been done by many researchers (Ritchie, 1972; Shuttleworth and Wallace, 1985; Lascano et al., 1987; Allen et al., 1998). Since the S–W model and FAO dual-K_c method are widely used, and have been validated to estimate ET components in different ecosystems (Hu et al., 2009, 2013; Er-Raki et al., 2010; Ding et al., 2013; Poblete-Echeverría and Ortega-Farias, 2013; Zhu et al., 2013, 2014), the two approaches were used to partition ET into soil evaporation and plant transpiration in a furrow-irrigated vineyard in this study.

The S–W model is an approach to directly estimate ET components based on two Penman–Monteith equations, i.e., one for the plant and the other for the soil surface (Monteith, 1965), and the two components are weighted by a set of coefficients that represent the combination of soil and canopy resistances (Shuttleworth and Wallace, 1985). This model provides the possibility to partition ET into plant and soil components through the use of surface resistances to regulate the transfer of energy from plants (r_s^c) and soil (r_s^s), and aerodynamic resistances (r_a^a, r_a^c, r_a^s) to regulate the transfer between these surfaces and the atmosphere (Farahani and Bausch, 1995). Compared to other direct models, the S–W model are more widely used for crops with a partial ground cover, such as orchards, and have achieved acceptable results (Ortega-Farias et al., 2007, 2010; Zhang et al., 2008, 2009; Hu et al., 2013). Like most models, S–W model has limitation due to the need of measured data above canopy and several hardly obtained input parameters in field condition.

Apart from the direct models, the Food and Agricultural Organization of the United Nations (FAO) has developed an indirect method to estimate ET (Doorenbos and Pruitt, 1977) and further developed in the Paper FAO-56, includes the single and dual crop coefficient methods (Allen et al., 1998). Unlike the single crop coefficient method that integrated both effects of plant transpiration and soil evaporation into a crop coefficient (K_c), the dual crop coefficient method allows to separate soil evaporation and plant transpiration and divide K_c into basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_e). Due to practical simplicity and robustness, and also a fewer data requirements than the other direct models, the FAO-56 dual crop coefficient method has been adopted and evaluated over several sparse crops, such peach orchard (Goodwin et al., 2006), apple orchard (Dragoni et al., 2004), olive orchard (Er-Raki et al., 2010) and vineyard (Poblete-Echeverría and Ortega-Farias, 2013). However, the straightforward adoption of generalized crop coefficients (K_{cb} or K_c) recommended by FAO-56 can lead to the errors in the estimation of ET and its components, because the dividing of crop growth period and associated crop coefficients are closely related to local climate and crop condition (Katerji and Rana, 2006; Poblete-Echeverría and Ortega-Farias, 2013). So the adjustment of crop coefficient curve based on locally observed data is needed to achieve accurate estimate of actual water requirement. Several researchers have improved the model performance by adjusting the recommended crop coefficient curves in FAO-56 (Rana and Katerji, 2008; Er-Raki et al., 2008, 2010; Poblete-Echeverría and Ortega-Farias, 2013).

Several studies have evaluated the models performance in partitioning ET into soil and plant components for sparse vegetation (Zhang et al., 2009; Er-Raki et al., 2010; Hu et al., 2013; Poblete-Echeverría and Ortega-Farias, 2013), mainly about FAO dual-K_c method and S–W model. However, there are fewer studies about the model evaluation using long-term independent measurements of ET and its components and the comparison of different models to partition ET. Therefore, the objective of this study was to evaluate the S–W model and FAO dual-K_c method in estimating evapotranspiration and its components in a furrow-irrigated Merlot vineyard under arid condition using the measurements of an eddy covariance system, micro-lysimeter and sap flow system during two growing seasons (2013 and 2014), respectively, so as to provide accurate estimation of evapotranspiration and its components in vineyard of northwest China.

2. Materials and methods

2.1. Study site

The study was carried out in a furrow-irrigated Merlot (*Vitis vinifera* L.) vineyard (37°52′N, 102°50′E, 1585 m a.s.l.), located at the Experimental Station of Water-saving in Agriculture and Ecology of China Agriculture University in the Shiyang river basin of northwest China during the 2013 and 2014 seasons. The grapevines were planted in east–west rows with a distance between and within rows of 2.7 m and 1.0 m in 1999. The grapevines were manually separated into two trunks at the ground surface and one trunk was considered the half vine. The grapevine branches were fixed on the three wires, and the wire heights were 0.5, 1.0 and 1.5 m, respectively.

The experimental site is located in a continental temperate zone, with a mean annual precipitation of 164.4 mm, annual temperature of 8 °C and annual sunshine duration of over 3000 h. Water is in severe shortage in this region, the groundwater table is below 25 m, and mean annual pan evaporation is about 2000 mm. The vineyard soil is irrigated desert soil (Siltigic-Orthic Anthrosols) and soil texture is sandy loam, with an average bulk density of 1.49 g cm^{-3} to a depth of 1.0 m. Field capacity and wilting point were 0.31 and 0.27, and 0.11 and 0.10 m^3 m^{-3} for the 0–1.0 m layer and 0–10 cm layer, respectively. The vineyard was furrow-irrigated with a trapeziform ditch on south side of each row, with the depth, bottom width and surface width of 30, 90 and 100 cm, respectively (Zhang et al., 2011). Grapevines were irrigated 6 times during whole growth stage, i.e., April 27, May 25, July 1, July 30, August 25 and October 13, 2013, and April 22, May 25, July 2, August 4, August 31 and October 18, 2014, and irrigation quota is 70 mm each time.

2.2. Measurements

2.2.1. Soil water content and leaf area index

Gravimetric soil water content to a depth of 1.0 m was determined every 4–6 d by the oven-drying method at an interval of 0.1 m, with six sampling points inside the vineyard, and then volumetric soil water content was calculated from gravimetric soil water content and bulk density of each layer. Volumetric soil water content at the depth of 0.1 m was continuously monitored using six ECH$_2$O sensors (5TE, Decagon Devices, Inc., USA) distributed in the ditch and ridge, and collected every 10 min using a data-logger (Environmental logging system, Decagon Devices, Inc., USA).

Leaf area index (LAI) was estimated as a function of shoot length to total leaf area (Ortega-Farias et al., 2007). In this study, LAI were calculated as:

$$\mathrm{LAI} = \frac{\sum_1^i \mathrm{LA_{sh}}}{A_v} \tag{1}$$

$$\mathrm{LA_{sh}} = -358.1 + 23.1L_{sh}(L_{sh} > 25\mathrm{cm}), \text{ or } -42.8 + 12.8L_{sh}(L_{sh} < 25\mathrm{cm}) \tag{2}$$

where LA$_{sh}$ is total leaf area per shoot (cm^2), A_v vine area (cm^2), i total shoot number per vine and L_{sh} shoot length (cm). To develop the correlation between LA$_{sh}$ and L_{sh}, a total number of 73 branches were randomly selected from the vineyard at initial and middle